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ONR Grant No. N00014-90-J-4077

Micro-Mechanics of Electrostrictors for Sonar Transducers

QUARTERLY REPORT

Period September 1, 1992 - November 30, 1992

Sponsored by

Office of Naval Research (ONR)

Submitted to:

Dr. Wallace A. Smith
Office of the Chief of Naval Research
800 North Quincy Street
Arlington, Virginia 22217-5000

Submitted by:

Thomas R. Shrout

Mr. Norman Meeks

Sei-Joo Jang

Dr. Wallace A. Smith

Materials Research Laboratory
Penn State University
University Park, PA 16802

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I. Introduction

This study focuses on the performance of electrostrictor-based actuators for Navy-type Sonar transducers, being synergistic with the parent program "Relaxor Ferroelectrics for Electrostrictive Transducers" (N00014-90-J-4077) and the three-year AASERT project on the classification of electrostrictors. As stated, electrostrictors have been classified into Types I-IV, analogous to piezoelectrics (e.g. Navy Type I, PZT-4). Based on the following requirements for Navy Sonar transducers:

- Large E-field induced strains ($\geq 0.3\%$)
- Operating temperature range = 0 - 30°C
- Minimal strain-E-field hysteresis (≤ 1 kHz)
- Low heating due to dielectric losses

the performance of the four types of strictors have been summarized in Table I.

From the results presented in Table I, it is clearly evident that Type-I [$Pb(B_1B_2)O_3$] strictors offer superior overall performance. What is not yet clear is how such materials will perform under pre-stress and high-frequency drive conditions. In other words: what are the micro-mechanical limitations an ultimate reliability of these materials?

In this quarterly report the remainder of the proposed PMN compositional modifications have been investigated for use in SONAR transducers. Additionally, multilayer actuator studies utilizing compositions developed in the parent program will be discussed.

II. Compositional Modifications (Dielectric and Polarization Behavior).

Presented in this section are the results of ongoing compositional modifications to Type I - PMN electrostrictors. Compositional modifications to develop nano-scale strain-property relationships of order-disorder phenomena will continue through the AASERT program.

The dielectric temperature behavior (at 1 kHz) for Ca-modified PMN ceramics are presented in Figure 1. As shown, T_{max} and K_{max} decrease markedly with increasing Ca-modification, while the transition width increases. The effects of Ca-modification on the polarization temperature behavior are presented in Figure 2. From this figure a strong depression of the depolarization temperature T_d is observed with increasing Ca-modification.

A plot of T_{max} - T_d versus % Ca- and K-modification is presented in Figure 3. The non-linearity of the Ca data suggests limited solubility of Ca^{2+} on the A-site in PMN ceramics. In contrast to Ca-modification, K-modification results in increased T_{max}-T_d.

The dielectric temperature behavior (1 kHz) for K-modified PMN-PT ceramics are presented in Figure 4. Again, as with other A-site modifications, T_{max} decreases with increasing K-modification.

The polarization temperature behavior for K-modified PMN-PT ceramics is presented in Figure 5. The depolarization temperature T_d is shifted downward with increasing K-modification. The pyroelectric peak broadens and reduces with increasing K-modification.

The dielectric and polarization data for Ca- and K-modifications are summarized in Table II. In both cases, the width of polar Regime II (T_{max} - T_d) increases with A-site modification. Plots of K_{max} (T_{max} - T_d)versus T_{max} for Ca- and K-modifications are presented in Figure 6. As seen in this figure, the slopes of the K_{max} versus T_{max} data are very similar for bothmodifications. However, different behavior is observed for the depolarization behavior: K-modification more strongly depresses T_d than Ca-modification.

Table I. Performance Summary of Electrostrictors for Sonar Transduces

Material Type	Example	Strain Level	Temp. Range	Hysteresis	Freq.* Dependency	Heating Loss	Elastic S_{ij}	Microstructural Dependency
Normal IV	$(Ba,Sr)TiO_3$	—	—	0	0,+	+	++	—
Type III	$Ba(Ti,Sn)O_3$	0	+	+	?	?	—	—
Relaxor II	PLZT	++	++	—	0, —	—	+	0
Relaxor I	PMN-PT	+	+	++	+	+	+	+
Piezo	PZT-4,8	+	+++	—	+	0	—	0
Type I, III								

* Subjective in relation to T_m.

+ - Best
0 - Moderate
— - Worst

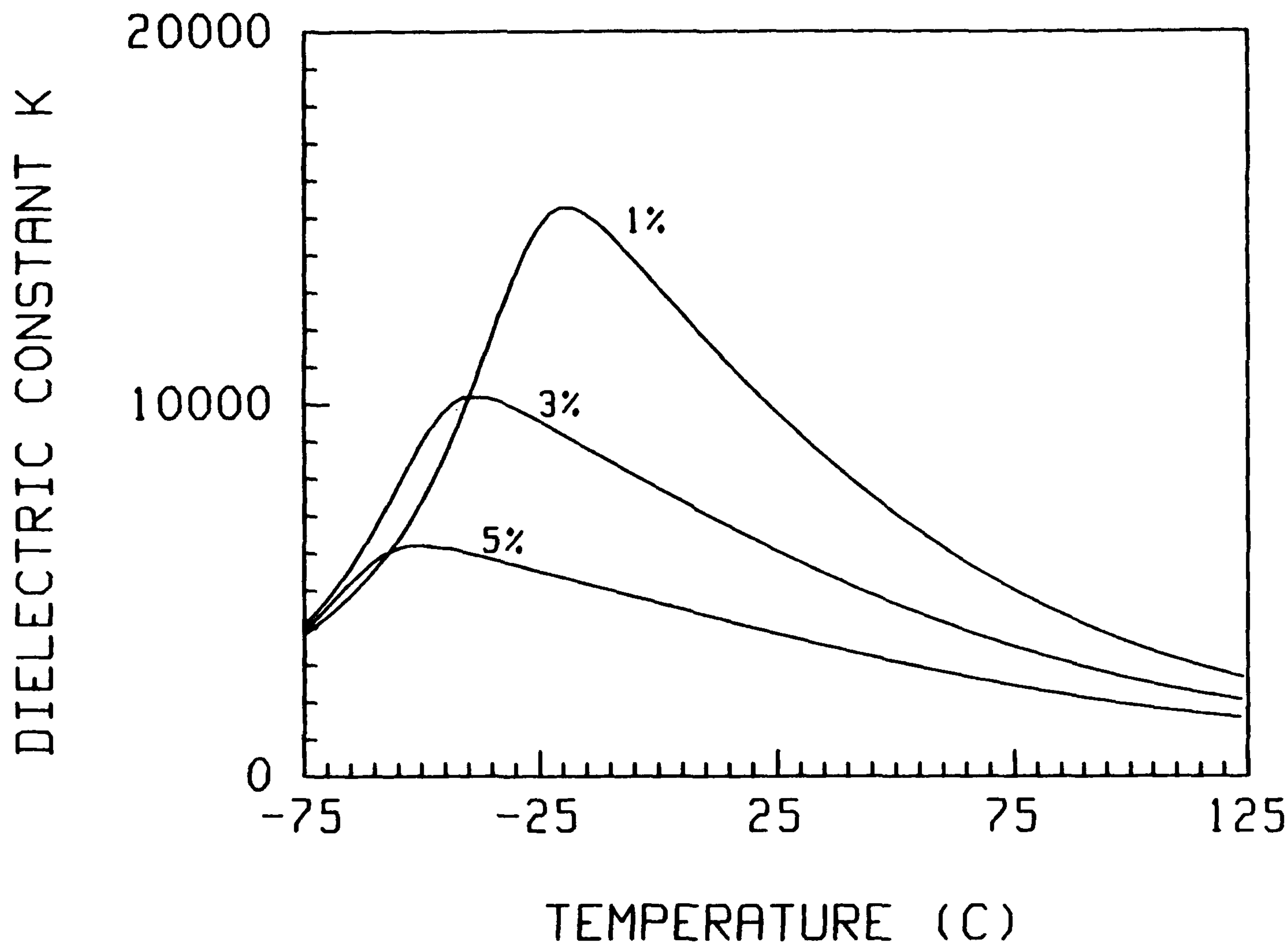


Figure 1. Dielectric temperature behavior for Ca-modified PMN compositions (1 KHz Data).

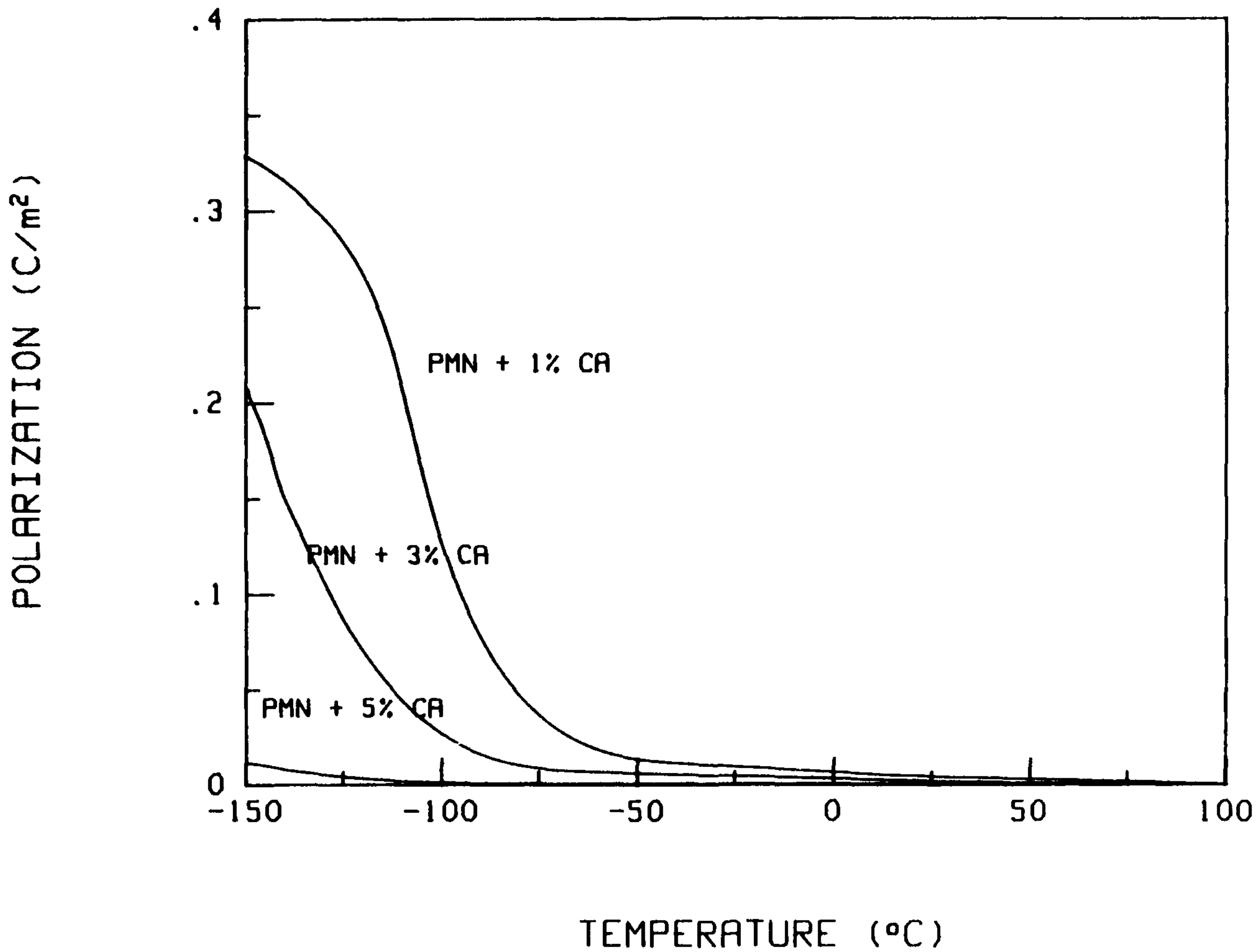


Figure 2. Polarization temperature behavior for Ca-modified PMN compositions.

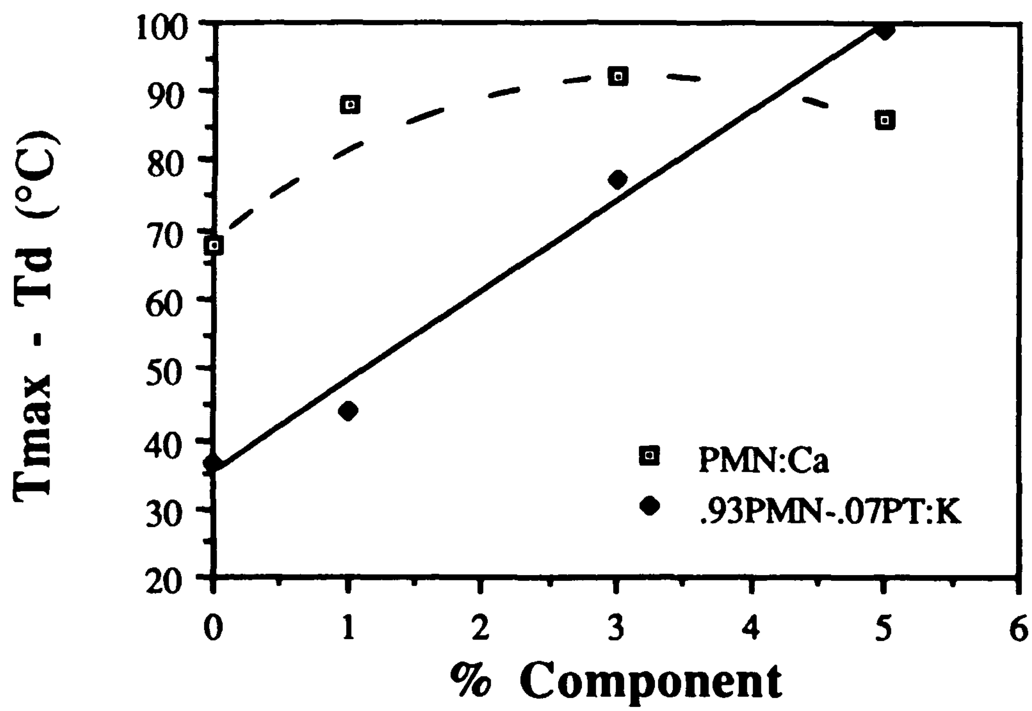


Figure 3. Width of Polar Regime II (T_{max}-T_d) as functions of Ca- and K-modifications to PMN-PT compositions.

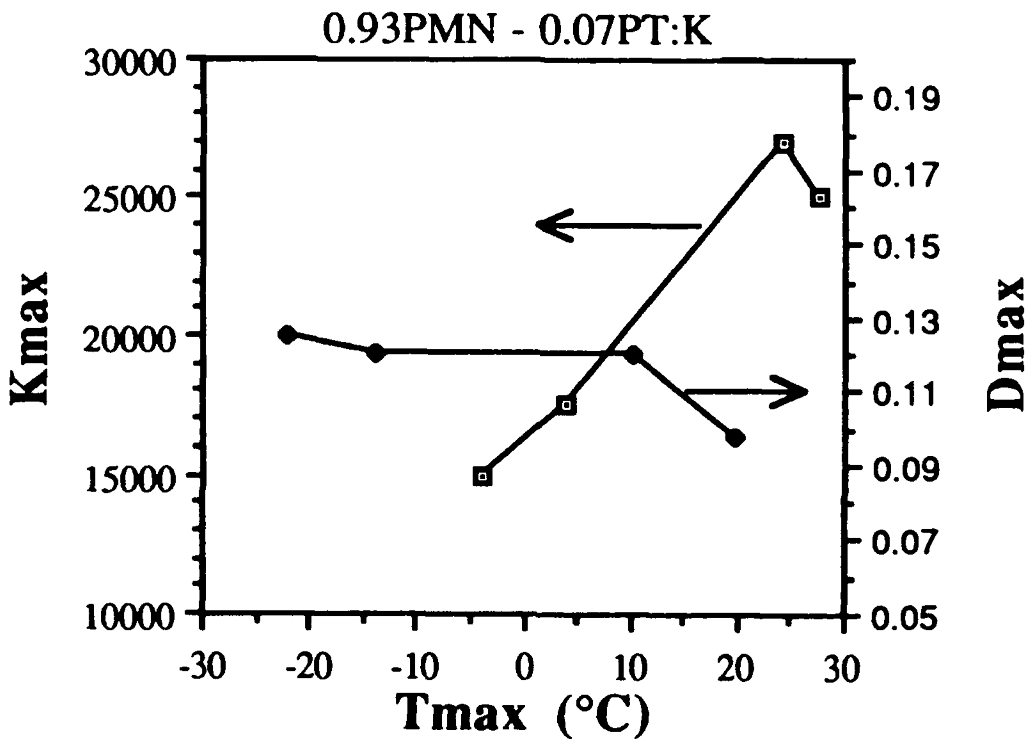


Figure 4. Dielectric temperature behavior for K-modified PMN-PT compositions (1 KHz data).

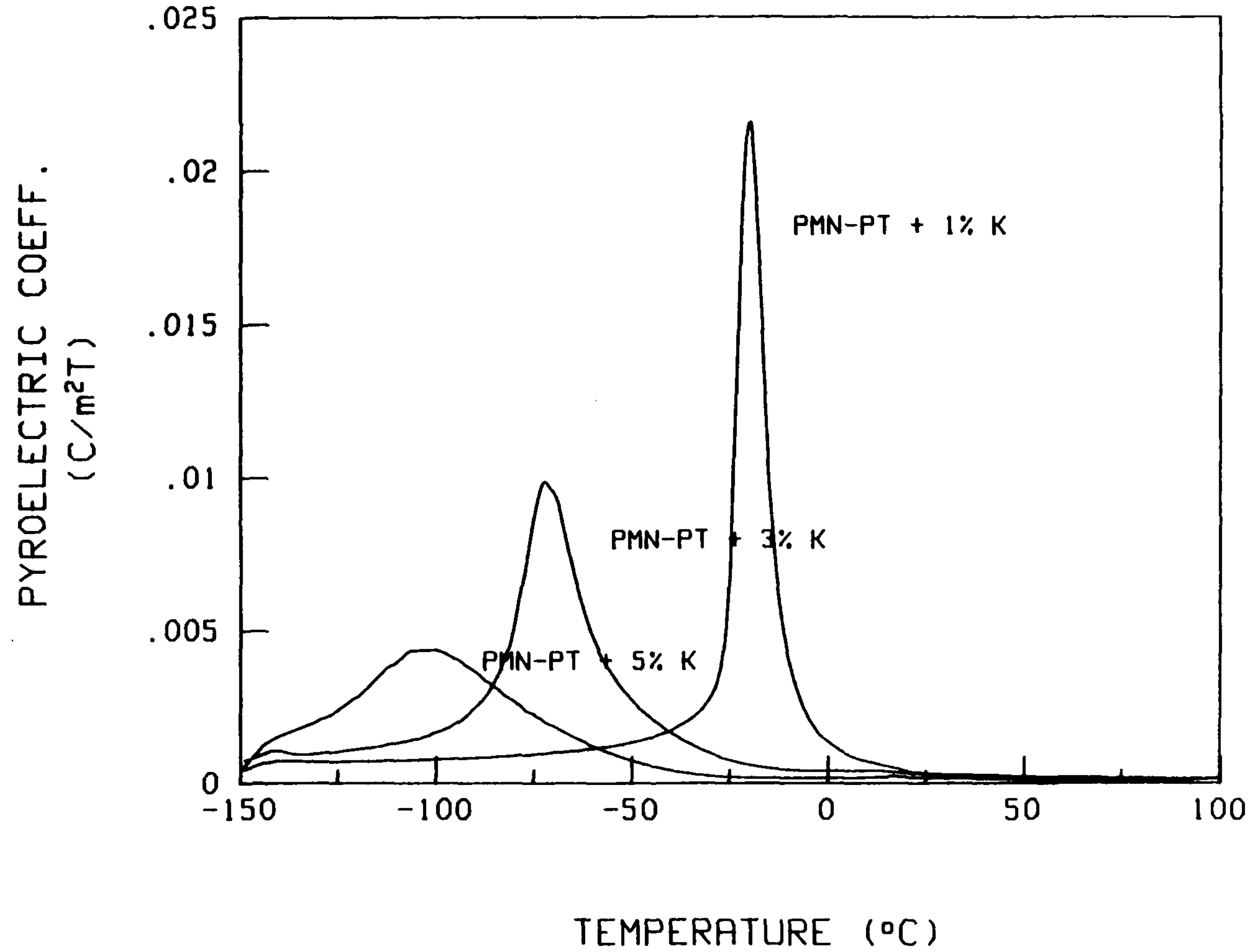


Figure 5. **Polarization temperature behavior for K-modified 0.93 PMN-0.07 PT compositions.**

Table II. Dielectric/Polarization Data for "New" Compositions.

Composition	T_{max} (°C) (1 kHz)	T_d (°C)	$T_{max} - T_d$ (°C)	K_{max} (1 kHz)	$\tan\delta_{max}$@°C (1 kHz)
K/PMN/PT					
1/93/7	24	-20	44	27,000	0.12@10
3/93/7	4	-73	77	17,500	0.12@-14
5/93/7	-4	-103	99	15,000	0.125@-22
Ca/PMN					
1%	-20	-108	88	15,200	
3%	-38	-130	92	10,300	
5%	-52	-138	86	7,200	

The dielectric property measurement of materials evaluated for SONAR applications allows some conclusions to be drawn. As previously reported, the combination of A- and B-site modifications to PMN ceramics results in T_{max}'s in the usage temperature range (through Ti-modification) and a broadened micro-macro polar Regime II (through A-site modifications). Thus, compositions exhibiting high induced polarization/strain behavior with minimal hysteresis over a broad temperature range are now realized. These data are compiled for reference in Appendix A.

III. Induced Polarization/Strain Behavior.

The induced polarization and transverse strain data for K- and Ca-modified PMN-PT ceramics are compiled in Table III. The Ca-modified PMN compositions, with T_{max}'s all well below 0°C show correspondingly low levels of induced polarization and strain. K-modified PMN-PT compositions exhibit greater levels than Ca-modifications, in agreement with their higher T_{max}'s. The levels of remanent strain and hysteresis are well within the specifications for SONAR-type applications within the usage temperature range.

The levels of induced polarization and transverse strain (at 20 kV/cm) as functions of temperature (within the proposed usage range) for Ca-modifications of 1, 3, and 5% are presented in Figure 7. As expected from the dielectric data, these levels are quite low for all evaluated compositions, and decrease with increasing Ca-modification.

The levels of induced polarization and transverse strain (at 20 kV/cm) as functions of temperature (within the proposed usage range) for K-modifications of 1, 3, and 5% are presented in Figure 8. These data are in good agreement with those from modified PMN-PT compositions having similar T_{max} values (see Appendix B).

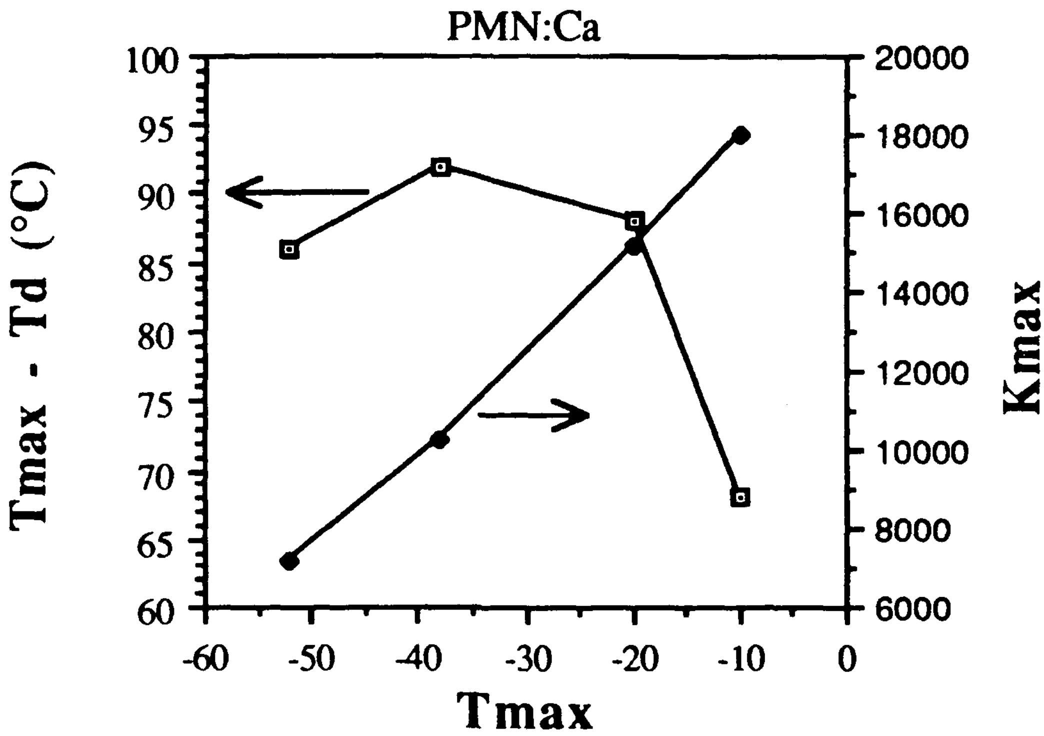
As with the other A-site compositional modifications investigated, T_{max} and T_d decrease while $T_{max} - T_d$ increases with increasing K- or Ca-modification. These effects are manifested in the induced polarization/strain behavior. Induced polarization and strain levels decrease with increasing modification due to depression of T_{max} below the usage range. Strain hysteresis is also decreased, due partly to reduction in T_{max} and partly to broadening of micro-macro polar Regime II.

Table III . Polarization/Strain Data for Additional Modifications to Type I electrostrictor PMN-PT.

Composition	Temp. (°C)	P_{ind} (C/m^2) 10 kV/cm	20 kV/cm	P_r (C/m^2)	Transverse Strain ($x10^{-6}$) 10 kV/cm	20 kV/cm	Remanent Strain ($x10^{-6}$)	Hysteresis (%)
PMN:1% Ca	40	0.059	0.104	0.003	15.5	54.5	≈0	≈0
	30	0.065	0.114	0.003	21.1	68.0	≈0	≈0
	20	0.075	0.126	0.003	26.7	84.3	≈0	3.3
	10	0.082	0.137	0.004	34.4	101	≈0	2.8
	0	0.092	0.149	0.005	40.4	118	≈0	4.2
	-10	0.104	0.166	0.009	52.7	141	≈0	4.0
PMN:3% Ca	40	0.047	0.088	0	9.8	32.0	0	0
	30	0.054	0.099	0.001	12.2	41.6	0	0
	20	0.059	0.109	0.001	15.5	48.9	0	0
	10	0.064	0.118	0.001	16.9	59.0	0	0
	0	0.073	0.129	0.001	22.5	68.9	0	0
	-10	0.078	0.138	0.001	26.0	86.6	0	0
PMN:5% Ca	40	0.033	0.062	≈0	4.2	15.7	0	0
	30	0.036	0.068	0	4.9	19.1	0	0
	20	0.039	0.074	0	6.3	23.0	0	0
	10	0.042	0.079	0	7.4	27.8	0	0
	0	0.046	0.085	0	8.4	31.8	0	0
	-10	0.049	0.091	0	10.1	36.8	0	0

.93PMN-.07PT:1% K	40	0.172	0.235	0	133	259	≈0	5.4
	30	0.204	0.258	0	173	309	≈0	4.5
	20	0.220	0.275	0	218	360	0	5.9
	10	0.248	0.289	0.003	270	407	≈0	5.9
	0	0.268	0.302	0.011	337	452	1.4	10.9
	-10	0.287	0.314	0.046	365	481	14.1	22.8
3% K	40	0.107	0.169	0	57.6	146	0	2.9
	30	0.122	0.186	0	74.5	177	0	3.9
	20	0.135	0.200	0	92.7	209	0	3.4
	10	0.149	0.214	0	112	242	0	4.1
	0	0.167	0.228	0	155	278	0	5.1
	-10	0.182	0.241	0	170	312	0	5.0
5% K	40	0.086	0.143	0	43.6	121	0	2.3
	30	0.096	0.157	0	52.0	143	0	3.9
	20	0.107	0.170	0	63.2	171	0	3.3
	10	0.12	0.183	0	77.3	200	0	3.5
	0	0.135	0.193	0	97.0	222	0	3.8
	-10	0.141	0.207	0	124	267	0	4.7

(a)



(b)

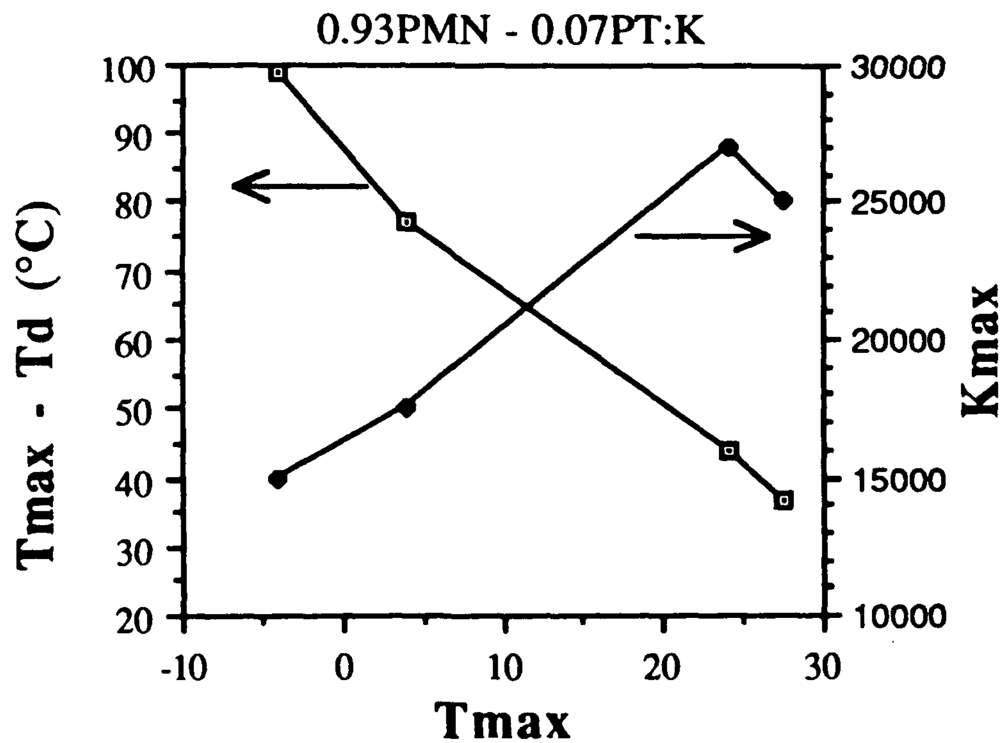


Figure 6. Maximum dielectric constant (K_{max}) (1 KHz data) and width of Polar Regime II (T_{max}-T_d) for (a) Ca-modified PMN and (b) K-modified 0.93 PMN-0.07 PT compositions.

(a)

(b)

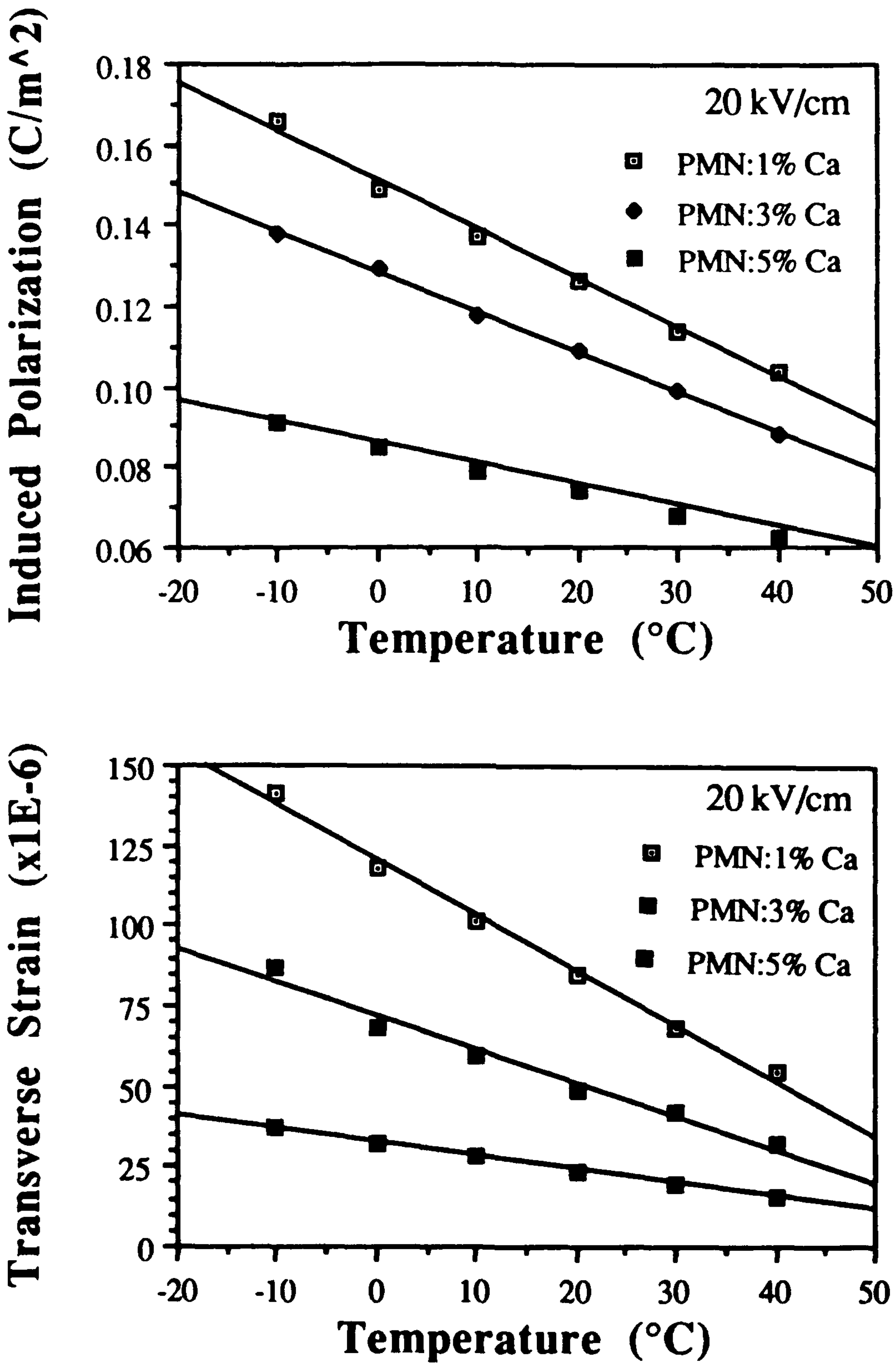
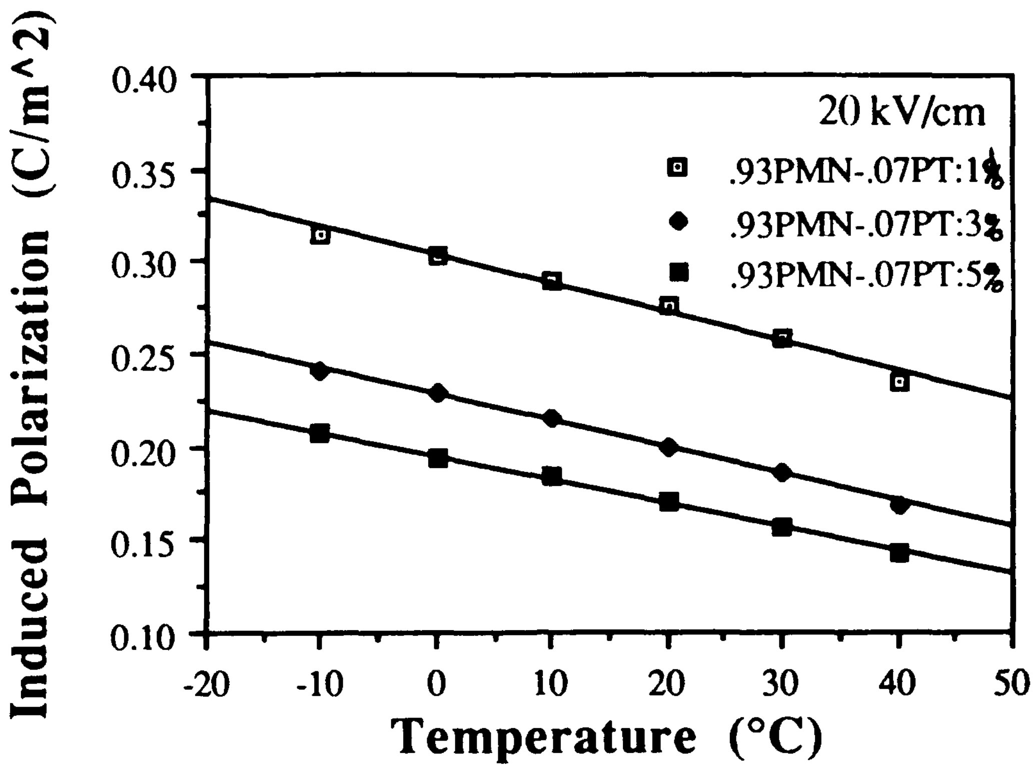


Figure 7. Levels of (a) induced polarization and (b) transverse strain at 20 KV/cm for Ca-modified PMN compositions.

(a)



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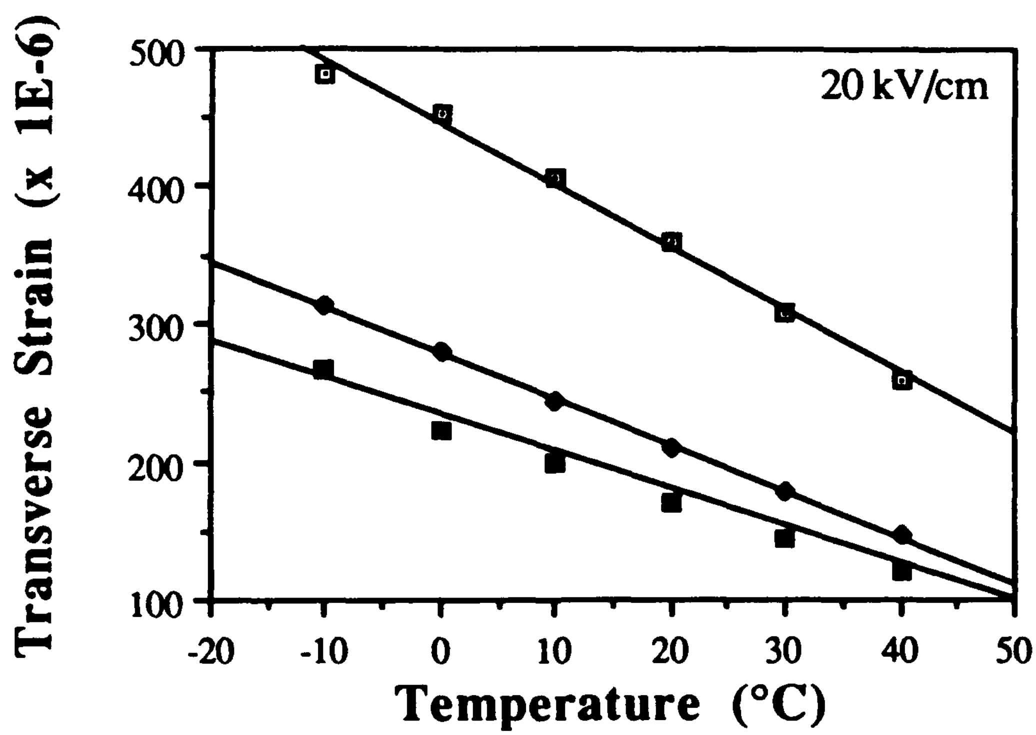


Figure 8. Levels of (a) induced polarization and (b) transverse strain at 20 KV/cm for K-modified 0.93 PMN - 0.07 PT compositions.

IV. Additional Data.

The effects of applied D.C. bias on the dielectric temperature behavior of a Type III electrostrictor $BaTi_{0.9}Sn_{0.1}O_3$ are presented in Figure 9. As shown, an applied field of 10 kV/cm depresses K_{max} to roughly 1/3 its zero-bias value while T_{max} is shifted upward slightly. This behavior is expected for a normal ferroelectric where the polarization is near saturation in the zero-bias condition. The effects of bias on the dielectric loss is also as expected, and quite similar to the data reported previously for the Type IV electrostrictor $Ba_{1-x}Sr_xTiO_3$.

V. Prototype Multilayer Sonar Transducer Fabrication

As previously noted: the most desirable electrostrictor materials for Sonar transducer applications are the A-site modified PMN-PT compositions (with $T_{max} \approx$ room temperature) and the PLZT compositions (10/65/35 and 11/65/35). The latter compositions may prove inferior for the proposed application due to internal heating during high-field high-frequency drive, as discussed in the final report for the parent program.

Efforts are ongoing in the production of large volumes of La-modified PMN-PT compositions for assembly into multilayer stacks.

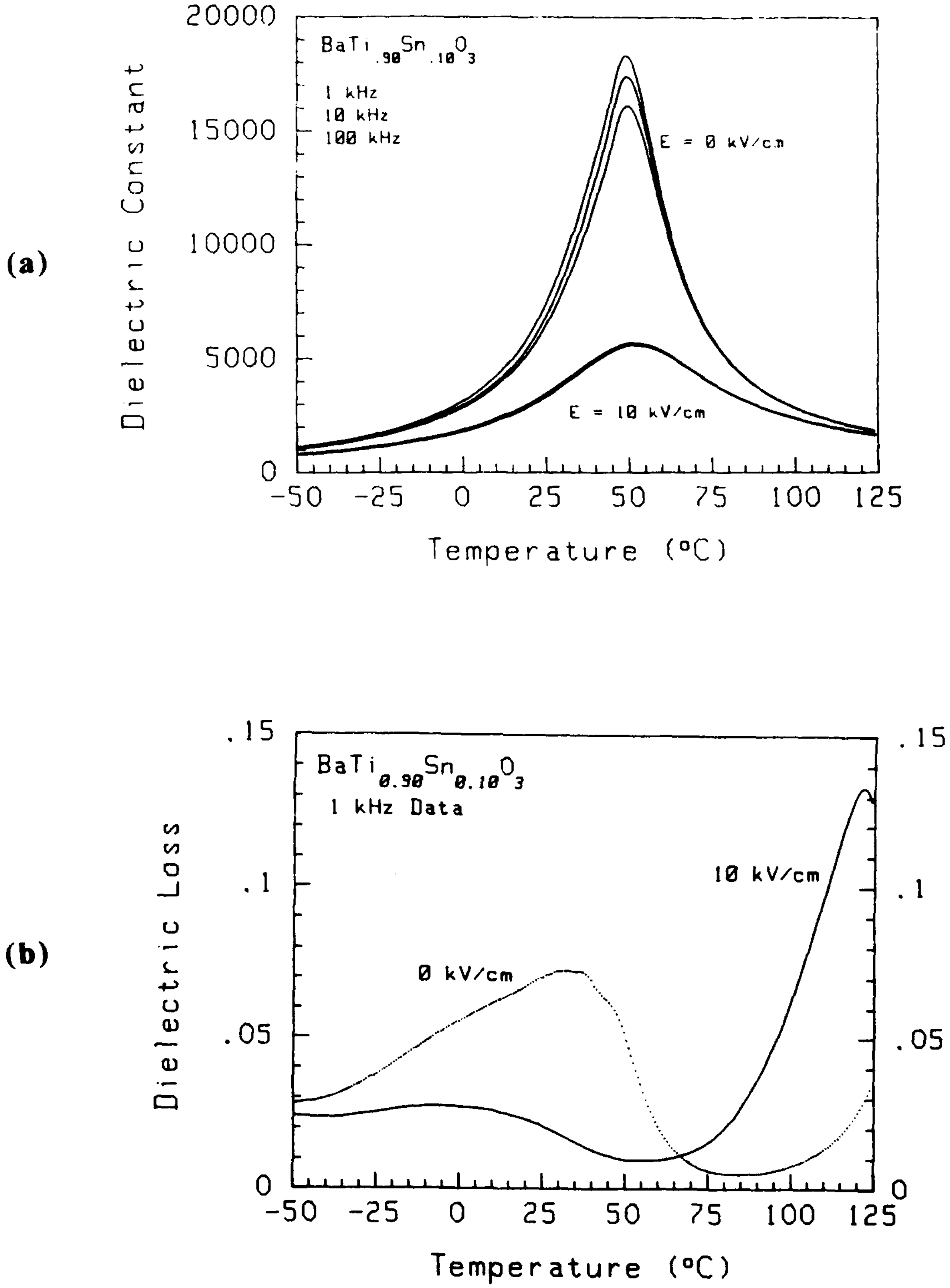


Figure 9. Effects of applied DC bias (10 KV/cm) on (a) dielectric constant temperature behavior and (b) dielectric loss temperature behavior of Type III electrostrictor $BaTi_{0.90}Sn_{0.10}O_3$ (1 KHz data).

Appendix A.

Table A1. Dielectric data for modified Type I relaxor PMN compositions.

Composition	T_{max} (1 kHz)(°C)	T_d (°C)	T_{max} - T_d (°C)	K_{max} (1 kHz)	tan δ_{max} (1 kHz)
PMN-PT					
PMN	-10	-78	68	18.0 x 10^3	0.1 @ -24°C
0.98PMN-0.02PT	5	-58	63	19	0.095 @ 11°C
0.97PMN-0.03PT	9.5	-45	54.5	21.5	0.09 @ 2°C
0.95PMN-0.05PT	17.5	-27	44.5	24.3	0.10 @ 12°C
0.93PMN-0.07PT	27.5	-9	36.5	25.0	0.095 @ 19.8
La/PMN/PT					
1/100/0	-35	--	--	14.4	0.11 @ -47°C
1/95/5	-7	-80	73	19.0	0.09 @ -15°C
1/93/7	5	-69	74	22.7	0.11 @ -9°C
7/65/35	13.5	-55	68.5	13.7	0.05 @ 7°C
4/73/27	34	-20	55	19.0	0.09 @ 20°C
3/79/21	25.5	-48	73.5	19.0	0.09 @ 14°C
2/85/15	17.5	-49.5	67	20.5	0.10 @ 5°C
1/91/9	12	-48	60	22.5	0.12 @ 0°C
Ca/PMN/PT					
1/100/0	-20	-108	88	15.2	--
3/100/0	-38	-130	92	10.3	--
5/100/0	-52	-138	86	7.2	--
Sr/PMN/PT					
1/93/7	9	-50.5	59.5	20.2	0.10 @ -5°C
3/93/7	-16.5	-115	98.5	18.4	0.12 @ -38°C
5/93/7	-23	-135	112	16.5	0.12 @ 44°C
Ba/PMN/PT					
1/85/15	59.5	23	36.5	22.9	--
3/85/15	39	29	10	18.4	--
5/85/15	19	--	--	17.5	--
K/PMN/PT					
1/93/7	24	-20	44	27.0	0.12 @ 10°C
3/93/7	4	-73	77	17.5	0.12 @ -14°C
5/93/7	-4	-103	99	15.0	0.12 @ -22°C

Table A2. Dielectric data for Type II relaxor PLZT compositions.

Composition	T_{max} (1 kHz)(°C)	T_d (°C)	T_{max} - T_d (°C)	K_{max} (1 kHz)	tan δ_{max} (1 kHz)
PLZT					
9/65/35	77	-31	108	7.8×10^3	0.06 @ 36°C
10/65/35	55	-69	124	7.12	0.08 @ 19°C
11/65/35	39	-102	141	5.31	0.08 @ 1°C

Table A3. Dielectric data for Type III "pinched" ferroelectrics $Ba(Ti_{1-x}Sn_x)O_3$.

Composition	T_{max} (1 kHz)(°C)	T_d (°C)*	T_{max} - T_d (°C)	K_{max} (1 kHz)	tan δ_{max} (1 kHz)
$Ba(Ti_{1-x}Sn_x)O_3$					
x = 0.10	48	38	10	29.0×10^3	0.055 @ -55°C
x = 0.13*	8	1,63	7,-55	32.5	0.09 @ 3°C

* Note: "Pinched" ferroelectric; multiple phase transitions in vicinity of T_{max}.

Table A4. Dielectric data for Type IV normal ferroelectric $(Ba_{1-x}Sr_x)TiO_3$.

Composition	T_{max} (1 kHz)(°C)	T_d (°C)	T_{max} - T_d (°C)	K_{max} (1 kHz)	tan δ_{max} (1 kHz)
$Ba_{1-x}Sr_xTiO_3$					
x = 0.35	25	25	0	26.0×10^3	--
x = 0.40	1	1	0	23.5	--
x = 0.45	-15	-15	0	23.5	--
x = 0.50	-31.5	-31.5	0	23.5	--

Appendix B.

Table B1. Induced polarization/transverse strain data for modified Type I relaxor PMN compositions.

Composition	Temp. (°C)	Polarization (C/m^2) 10 kV/cm	20 kV/cm	Transverse Strain ($x10^{-6}$) 10 kV/cm	20 kV/cm	Hysteresis %
PMN-PT 85/15	-28.5			323	419	11.5
	-10			269	358	9.8
97/3	33	0.11	0.175	55	165	11.4
	30	0.11	0.175	70	180	8.9
	10	0.13	0.198	80	195	14.5
	26			52	130	9.2
	-30			100	235	18.8
	-4	0.149	0.211			
	-8			95	240	17.3
	-9	0.152	0.221			
93/7	-8	0.205	0.234	320	420	10.2
	0	0.215	0.254	280	395	6.4
	35	0.185	0.234	215	345	5.8
	-3	0.238	0.268	315	415	9.2
	18	0.202	0.269	300	415	6.5
	23	0.225	0.269	270	380	6.4
95/5	-50	0.28	0.317			
	25	0.181	0.237			
	-17	0.225	0.293			
	0			184	267	8.1
	3	0.225	0.268	187	295	11.5
	-13			216	273	25.2
	-20.5	0.237	0.286			
	12	0.205	0.258			
	14			170	236	4.1
	26	0.142	0.206	117	201	4.3
	22			170	235	4.2
	21			184	237	4.4

Table B1. (cont'd).

La/PMN/PT 2/85/15	5	0.1797	0.2405	199	371	6.0
	25			152	307	3.4
	0			217	392	9.1
	-26			267	407	27.0
	19			136	282	
4/73/27	1.5	0.205	0.2474			
	26	0.1718	0.2295	223	403	2.6
	10.5	0.188	0.2346	291	470	7.5
	-4	0.2141	0.25			
	-27	0.234	0.2705			
	0			354	522	12.9
	-5			358	549	17.0
1/93/7	21	0.101	0.181	95	210	<1
	-32	0.176	0.243			
	-1	0.137	0.216			
	-10	0.141	0.210			
	-32	0.208	0.275			
	-29	0.208	0.265			
	22	0.134	0.204			
	24			95	215	<2
	-12			212	340	6.0
	1			135	270	3.0
	-27			248	366	8.5
	-19			263	324	34.0
Sr/PMN/PT 1/93/7	-43	0.216	0.26	235	380	15.9
	27	0.142	0.207	95	230	12.0
	4	0.180	0.236	156	325	17.1
	-8	0.190	0.243	190	335	13.5
	8	0.144	0.207	105	235	10.3

Ca/PMN/PT 1/100/0	40	0.059	0.104	15.5	54.5	0
	30	0.065	0.114	21.1	68.8	0
	20	0.075	0.126	26.7	84.3	3.3
	10	0.082	0.137	34.4	101	2.8
	0	0.092	0.149	40.4	118	4.2
	-10	0.104	0.166	52.7	141	4.0
3/100/0	40	0.047	0.088	9.8	32.0	0
	30	0.054	0.099	12.2	41.6	0
	20	0.059	0.109	15.5	48.9	0
	10	0.064	0.118	16.9	59.0	0
	0	0.073	0.129	22.5	68.9	0
	-10	0.078	0.138	26.0	86.6	0
5/100/0	40	0.033	0.062	4.2	15.7	0
	30	0.036	0.068	4.9	19.1	0
	20	0.039	0.074	6.3	23.0	0
	10	0.042	0.079	7.4	27.8	0
	0	0.046	0.085	8.4	31.8	0
	-10	0.049	0.091	10.1	36.8	0
K/PMN/PT 1/93/7	40	0.172	0.235	133	259	5.4
	30	0.204	0.258	173	309	4.5
	20	0.220	0.275	218	360	5.9
	10	0.248	0.289	270	407	5.9
	0	0.268	0.302	337	452	10.9
	-10	0.287	0.314	365	481	22.8
3/93/7	40	0.107	0.169	57.6	146	2.9
	30	0.122	0.186	74.5	177	3.9
	20	0.135	0.200	92.7	209	3.4
	10	0.149	0.214	112	242	4.1
	0	0.167	0.228	155	278	5.1
	-10	0.182	0.241	170	312	5.0
5/93/7	40	0.086	0.143	43.6	121	2.3
	30	0.096	0.157	52.0	143	3.9
	20	0.107	0.170	63.2	171	3.3
	10	0.120	0.183	77.3	200	3.5
	0	0.135	0.193	97.0	222	3.8
	-10	0.141	0.207	124	267	4.7

Table B2. Induced polarization/strain data for Type II relaxor PLZT (x/65/35).

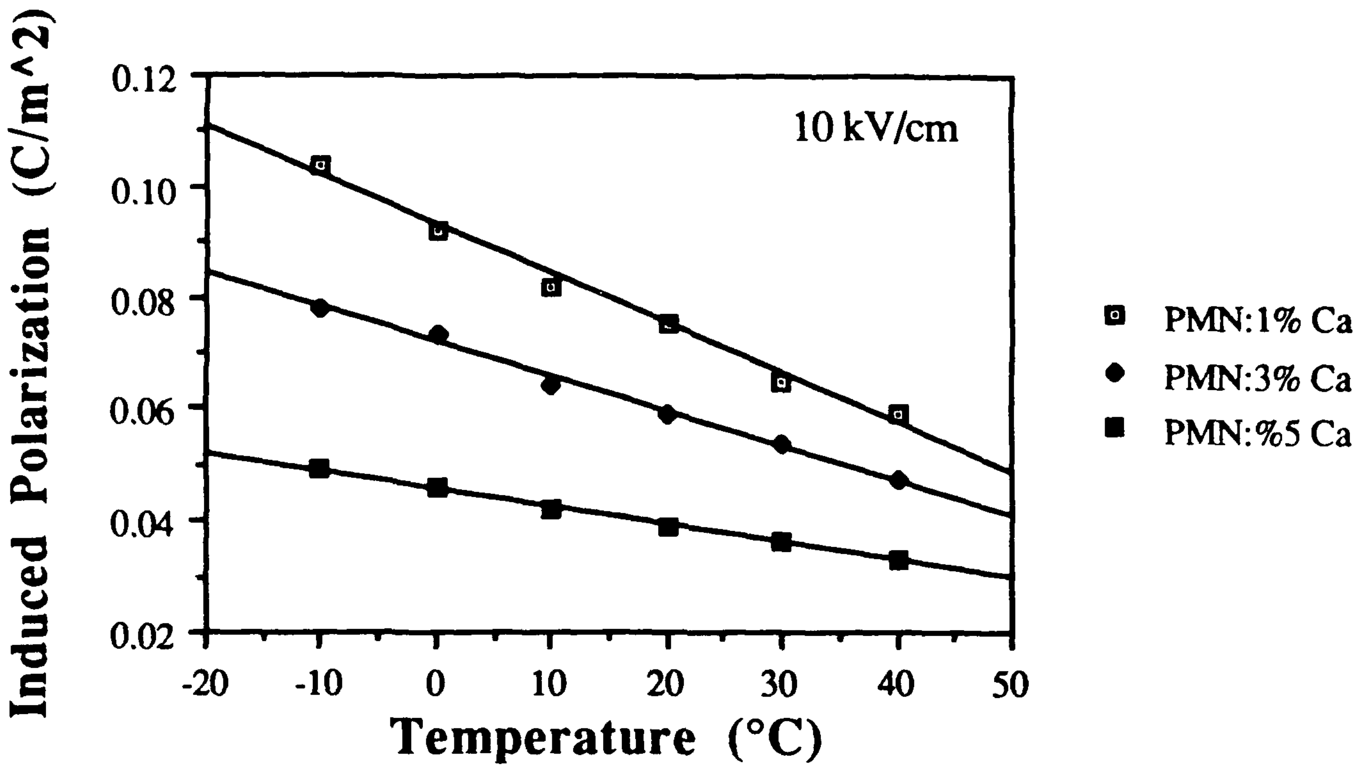
Composition	Temp. (°C)	Polarization (C/m^2) 10 kV/cm	20 kV/cm	Transverse Strain ($x10^{-6}$) 10 kV/cm	20 kV/cm	Hysteresis %
PLZT 9/65/35	22	0.245		580		40.0
	20	0.226				
	17			540		50
	14			590		43.1
	12	0.255		610		53.2
	10	0.24		615		43.6
	6	0.245		690		53.3
	4			655		61.7
	1	0.248		670		67.1
	-36			940		80
	2			700		64.3
	26	0.238	0.297	433	725	23.9
	40	0.212	0.290	383	708	9.4
10/65/35	23	0.046	0.088	85	315	5.7
	4	0.053	0.101	110	380	8.2
	-16	0.056	0.109	130	460	13.6
11/65/35	24	0.171	0.207	190	315	2.3
	18	0.167	0.206	225	320	3.4
	13	0.181	0.208	220	350	4.3
	10	0.187	0.211	230	360	
	0	0.197	0.229	255	275	4.1
	-7			270	395	5.3

Table B3. Induced polarization/strain data for Type III "pinched" ferroelectric $Ba(Ti_{1-x}Sn_x)O_3$.

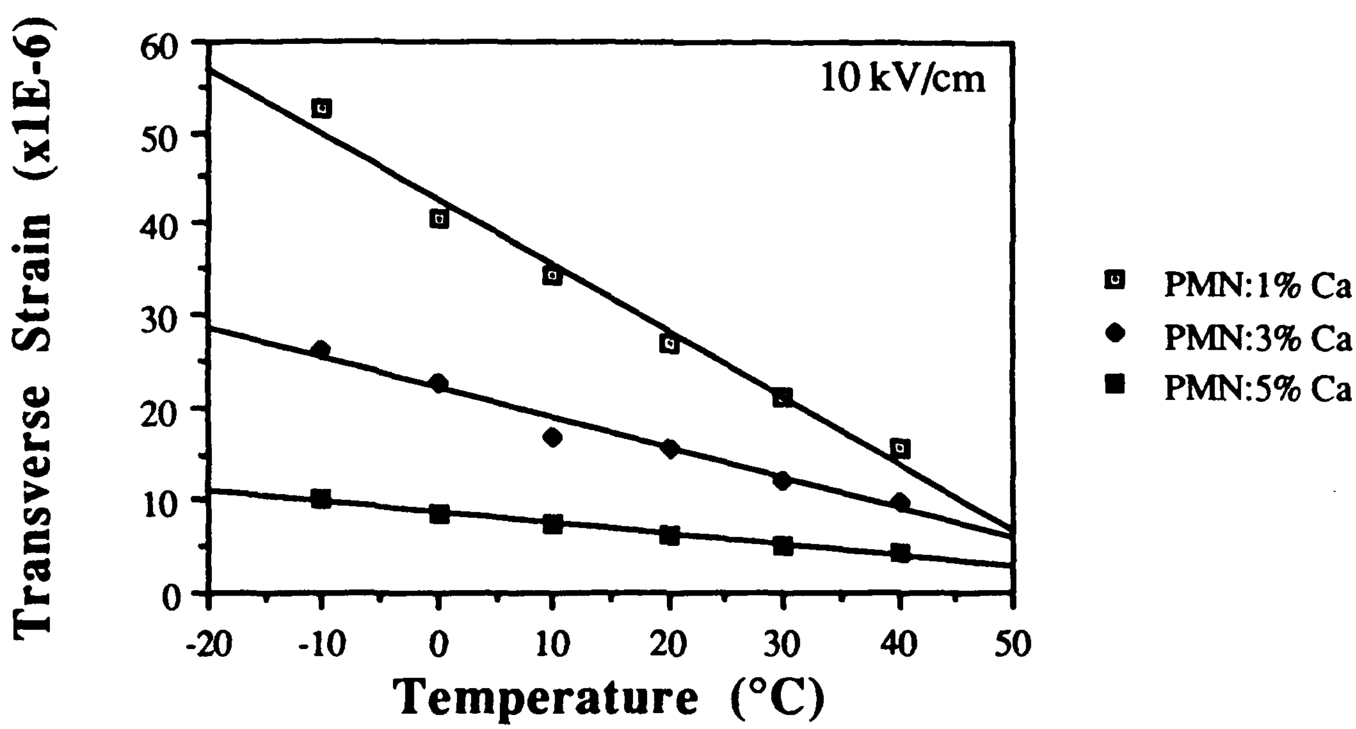
Composition $Ba(Ti_{1-x}Sn_x)O_3$	Temp. (°C)	Polarization (C/m^2) 10 kV/cm	Polarization (C/m^2) 20 kV/cm	Transverse Strain ($x10^{-6}$) 10 kV/cm	Transverse Strain ($x10^{-6}$) 20 kV/cm	Hysteresis %
x = 0.13	25	0.061	0.089	46.4	90	5.3
	-15	0.099	0.116	113	146	12.2
	-36			97	149	12.3
	-46	0.135	0.141	96	149	13.4
	-110			35	59	13.5
	-31	0.114	0.133			
	-59	0.110	0.137			
	-106	0.075	0.098			
x = 0.10	-40	0.118	0.146			
	-33	0.122	0.150			
	-26	0.124	0.144			
	-20	0.118	0.144			
	-6	0.106	0.134			
	1	0.106	0.132			
	30	0.106	0.128			
	40	0.089	0.115			
	45	0.085	0.111			
	-14	0.111	0.138	166	259	20.2
	5	0.108	0.132			
	24	0.079	0.094			
	-17			157	247	20.5
	-8			166	247	17.1
	1			158	247	17.5
	4			160	255	16.1
	24			159	241	12.5
	36			112	176	8.9
	43			85.3	143	6.1
	50			50	100	<1
	52			61	116	<1
	-36			177	278	39.5
	6			155	243	16.2
	21			133	215	9.5

Table B4. Induced polarization/strain data for Type IV ferroelectric $(Ba_{1-x}Sr_x)TiO_3$..

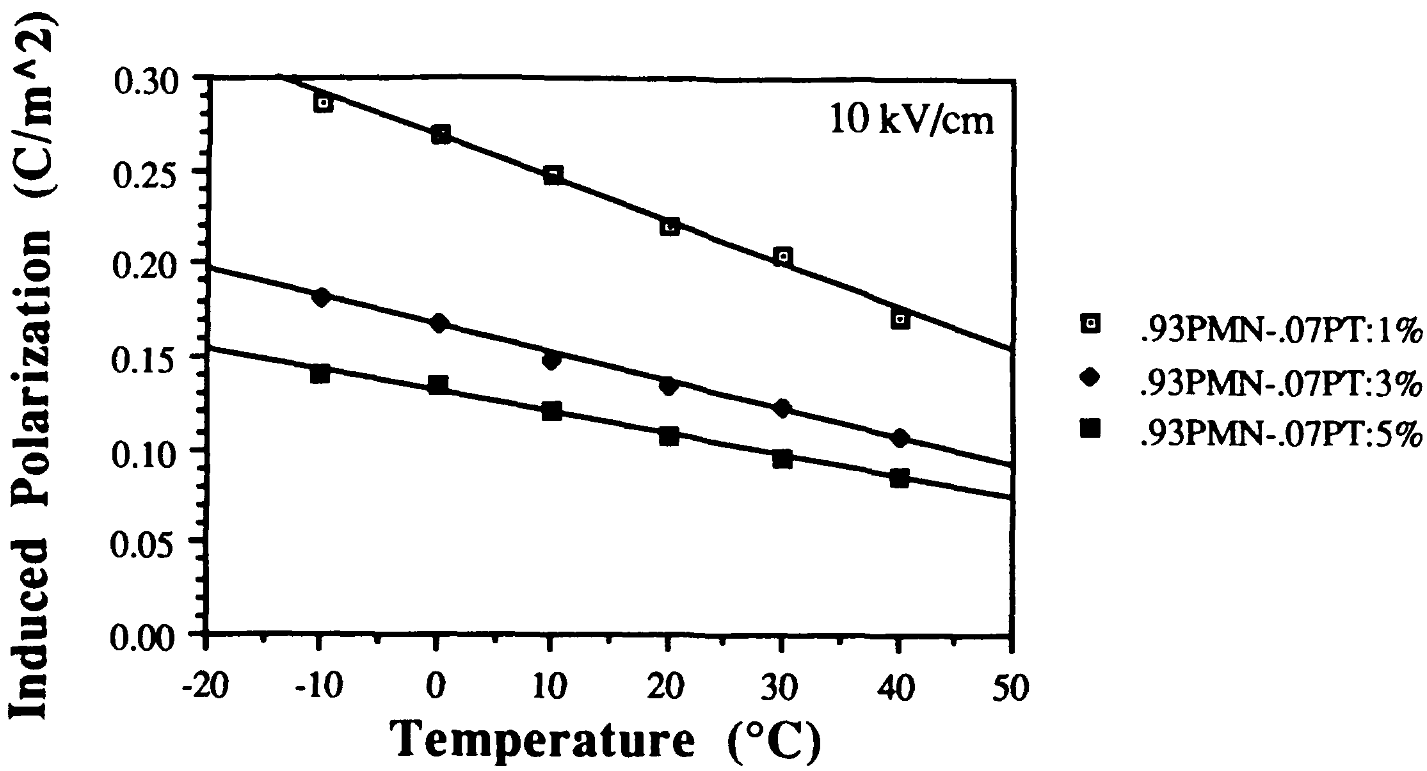
Composition	Temp. (°C)	Polarization (C/m^2) 10 kV/cm	20 kV/cm	Transverse Strain ($x10^{-6}$) 10 kV/cm	20 kV/cm	Hysteresis %
$Ba_{1-x}Sr_xTiO_3$ x = 0.35	26	0.055	0.082	55	115	<1
	23			64	129	<1
	14	0.079	0.1012	106	170	6.7
	10			152	226	9.8
	6			154	280	9.9
	4	0.0859	0.1051			
	-2	0.092	0.1077			
	-43	0.118	0.143	300	484	22.8
	-50			294	495	33.0
	-58			230	350	20.7
	-64	0.125	0.148	198	276	9.9
x = 0.45	22	0.027	0.046	8.5	23	<1
	-8	0.078	0.105			
	-12	0.100	0.118			
	-24	0.107	0.135			
	-29	0.115	0.143			
	-36	0.120	0.150	189	310	13.9
	-78	0.165	0.188	212	344	22.5
	-88	0.172	0.193			
	-74			175	270	14.6
	-32			187	304	11.0
	-3			30	70	2.4
	-18			160	235	12.1
x = 0.50	22	0.016	0.032			
	10	0.021	0.037			
	-12	0.036	0.064			
	-16	0.047	0.071			
	-22	0.049	0.077			
	-46	0.093	0.116			
	-52	0.110	0.137			
	-47			134	226	11.6
	-51			142	235	7.5



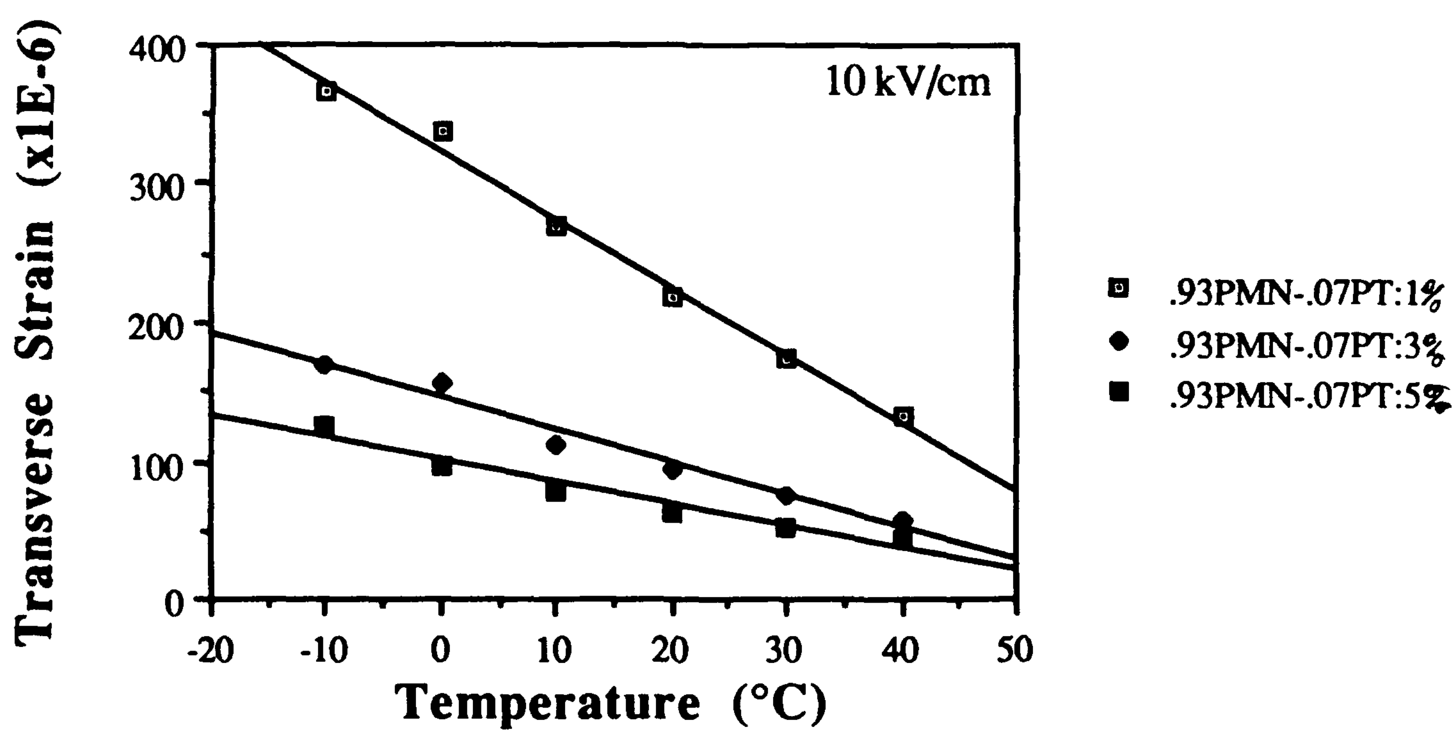
Induced Polarization (C/m^2)
0.12
0.10
0.08
0.06
0.04
0.02
10 kV/cm
-20
-10
0
10
20
30
40
50
Temperature (°C)
PMN:1% Ca
PMN:3% Ca
PMN:%5 Ca



Transverse Strain (x1E-6)
60
50
40
30
20
10
0
10 kV/cm
-20
-10
0
10
20
30
40
50
Temperature (°C)
PMN:1% Ca
PMN:3% Ca
PMN:5% Ca



Induced Polarization (C/m^2)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
10 kV/cm
-20
-10
0
10
20
30
40
50
Temperature (°C)
.93PMN-.07PT:1%
.93PMN-.07PT:3%
.93PMN-.07PT:5%



Transverse Strain (x1E-6)
400
300
200
100
0
10 kV/cm
-20
-10
0
10
20
30
40
50
Temperature (°C)
.93PMN-.07PT:1%
.93PMN-.07PT:3%
.93PMN-.07PT:5%